The Sense Resistor

in step-up converters

By K.-J. Thiesler

Sense resistors in series with the load are central to regulating current in switch-mode power supplies. It is possible to optimise the power loss in these resistors, as we show with an example converter circuit that drives eight white LEDs from a 4.8 V battery.

Switch-mode regulator ICs generally include a reference voltage generator and a differential amplifier. This combination is used to compare the voltage dropped across an external sense resistor with the reference and then suitably drive the output stage. The voltage drop across the resistor must be of the same order of magnitude as the reference, which in modern DC-DC converters is around 1.2 V. However, particularly when high currents are involved, this can mean an unreasonably large amount of power is wasted. With the following elegant circuit we can reduce the voltage drop across the sense resistor and hence reduce the power wastage.

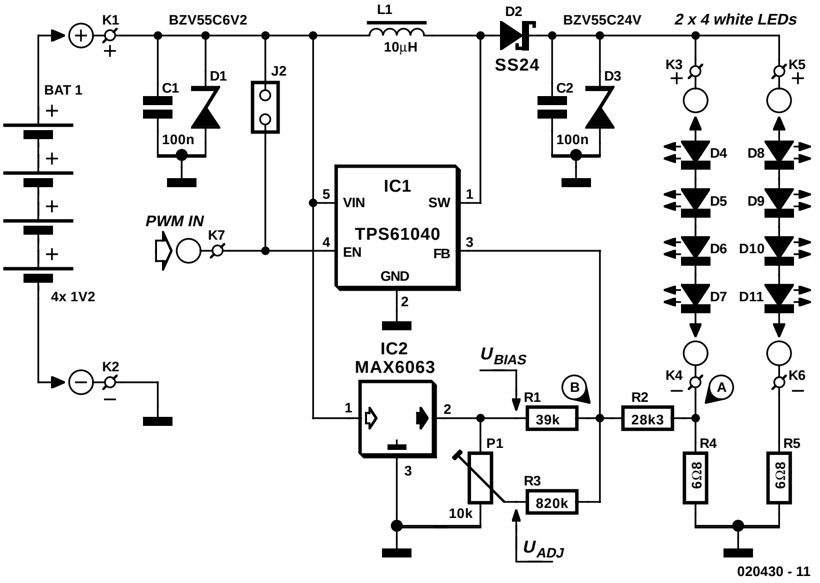

Figure 1. Modified step-up converter.

Key points

Figure 1 shows a typical switching regulator configured to drive eight white LEDs from a 4.8 V battery supply. The switching regulator has to produce a voltage $U_{LED\ BIAS}$ across the LEDs of nominally 4 _ 3.5 V = 14 V. The voltage actually required in practice is not important here, since the LEDs are driven with a regulated current rather than at a regulated voltage. A DC current of nominally 40 mA should flow through each chain of LEDs.

Resistor R4 serves here as the sense resistor: the voltage U_A, which depends on the LED current, is brought to the feedback pin (pin 3) of the switching regulator IC as U_{FB}. The output is controlled so as to make the feedback voltage 1.233 V. In standard applications point A is connected directly to pin 3. Then $U_{FB} = U_A = R4 \cdot I_{LED}$, and the power dissipated in R4 can be calculated as follows: $P_{R4} = U_A \cdot I_{LED} = R4 \cdot I_{LED}^2$. With a feedback voltage of 1.233 V we require a sense resistor of around 30 Ω, and the power dissipated in it will be 50 mW.

The alternative circuit uses a resistor R2 in series with the feedback connection. A constant voltage source of U_{BIAS} = 3.000 V (generated by a MAX6063) is connected to point B via R1. Now, in order to generate a feedback voltage of 1.233 V, we require a much lower sense voltage at point A. Resistor R4 can be reduced significantly (to a theoretical value of 7 Ω), and the power dissipated in it is correspondingly reduced.

The circuit with the auxiliary voltage reference generator also gives us a simple way to adjust the output current. To do this we also connect up a further voltage source U_{ADJ}, adjustable from 0 V to 3 V, via R3.

In order to calculate the resistor values, we start from the fact that a current of 45.3 µA will be flowing in R1 (39 kΩ). If U_{ADJ} is set at 1.233 V, then no current will flow in R3 and so this path will not have any effect on the circuit: all the current flowing in R1 will flow through R2. From the graph in **Figure 2** we can see that a voltage U_A of 144 mV corresponds to a voltage U_{ADJ} of 1.233 V, and so R2 should have a value of 24 kΩ.

The LED current should be adjustable from 0 mA to 50 mA. This corresponds to a voltage across R2 from 144 mV lower to 206 mV higher than the value just considered. To achieve the latter, R3 must draw a current of 206 mV/24 kΩ = 9.58 µA to ground. This means R3 should be 144 kΩ.

In order to calculate all the values exactly we can use Kirchhoff's current law, which states that the sum of the currents into a junction (here point B) is zero.

Analogue or PWM?

With U_{ADJ} at 3 V the switching converter stops operation and its quiescent current in this mode is 28 µA. With U_{ADJ} at 0 V the converter operates at its maximum frequency and the LEDs light at full brightness. Using this analogue control signal we can obtain adjustable brightness with good EMI emissions characteristics since there are no edges of a PWM control signal to get through to the LEDs. What may be a disadvantage is that the varying current through the LEDs results in a change in the emitted colour: the wavelength of the light emitted by an LED is dependent on the bias current. It is necessary to decide whether this shift in colour will be acceptable or not in each individual application. If analogue control of the output current is not desired, then connect U_{ADJ} directly to U_{BIAS} or simply omit the circuit involving R3 altogether.

Brightness control without affecting the resulting colour can be achieved using PWM. To this end the enable pin EN of the regulator should not be connected to the battery voltage: remove jumper J2 and instead drive EN from an external PWM signal via K7. This way it is possible not only to control the brightness from 0 % to 100 % in 'current mode', but also to exploit the brightness-enhancing effect of using double the nominal current pulsed at a frequency of 1 kHz with a duty cycle of 10 %. This gives the subjective effect of ten times the expected light intensity. In this case the values for R1, R2 and R4 need to be recalculated. At such a high current the voltage drop across a white LED can rise as high as 5 V, and this should also be taken into account. See also the article 'LED Arrays' in the April 2003 issue of *Elektor Electronics*.

The disadvantage of this method is of course that the LED current is pulsed and so the EMI characteristics are worsened. To mitigate this the LEDs should be mounted directly next to the regulator and the connections should be kept as short as possible. The datasheet recommends using a frequency of 100 Hz to 500 Hz at the enable input in PWM mode. In fact somewhat higher frequencies of 1.5 kHz to 2.5 kHz (but no higher) are more efficient. Below 100 Hz the pulses of light are visible to the eye. A PWM signal at a frequency of 1 kHz and an adjustable duty cycle in the range 0 % to 10 % is optimal both for the switching regulator and for the LEDs.

Components

Of course, the circuit as presented here is only a building block. Control circuitry, reverse polarity protection and overvoltage protection on the inputs all need to be added. Then the circuit has to be tested in practice. It's therefore worthwhile to take a brief look at the components used in the circuit.

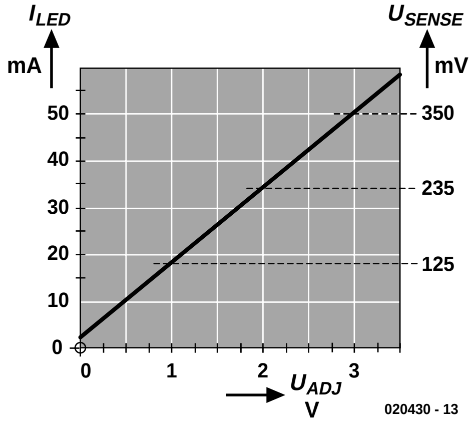

Figure 2. Effect of potentiometer voltage on LED current.

		Standard	Modified
LED current	mA	40	
$U_{LED\ BIAS}$: 4 LEDs	V	14	
P_{LED}	mW	560	
U_{FB}	V	1.233	
U_A	V	1.233	0.387
R4 (E24 series)	Ω	30	10
P_R SENSE	mW	51	17
$P_{MAX6063}$	mW	0	0,5
P_{TOT}	mW	611	577.5
Efficiency	%	91.7	97.6

The key component is the TPS61040 step-up converter, in an SMD package. The efficiency of this device when used as a current source is between 70 % and 85 %. The output voltage can go as high as 28 V, and so it is capable of driving up to six white LEDs. Internally the devices uses two-point regulation, and it can operate reliably with an output capacitor of only 100 nF. The peak current is regulated using pulse frequency modulation at a frequency of up to 1 MHz and the interval between pulses is guaranteed to be at least 400 ns. Stable operation with such a small output capacitor is only possible at such a high switching frequency. The voltage at the FB input is monitored using an internal comparator. The reference voltage U_{REF} is 1.233 V.

The internal power switch is turned off when the current through the coil exceeds 400 mA: this is the second point of regulation. The next pulse is started when the minimum interval between pulses of 400 ns has expired and the sense voltage U_{FB} has fallen below the sense voltage reference U_{FB}.

This regulation scheme runs in discontinuous mode, which means that as soon as the two criteria mentioned above are met the next cycle starts. The PFM switching frequency is therefore dependent on the input voltage, the output voltage, the inductance and the output current. The maximum pulse width is 6 µs. This way the device achieves its very high efficiency, without using external MOSFETs, over the entire range of load currents, and the tolerance of the coils and output capacitors is not critical to operation.

The switching current through the N-channel MOSFET is internally limited to a maximum of 400 mA in this modern IC, which effectively prevents possible saturation of the coil by limiting the duration of the PFM pulses. Naturally the device features ‘soft start’ and can operate reliably at full load even with batteries that are practically exhausted. In the first group of pulses the current through the switching transistor is limited to one quarter of its maximum value; in the next group to one half of its maximum; and then after 512 pulses the full current is allowed to flow. If the input voltage falls below 1.5 V the internal MOSFET is switched off.

The effective series resistance of the output capacitor C2 has a significant effect on the efficiency and switching behaviour of this type of boost converter circuit. Normally a ceramic capacitor is required, but the TPS6104x can also manage with inexpensive tantalum capacitors. If a value greater than 100 nF is chosen — as would be required in applications where low output noise is important — the EMI emissions characteristics are made worse.

For the switching diode, a Schottky type with low leakage current is called for. The SS24 SMD diode in a type B package (DO-241 AA) from Fairchild is readily available and has a low forward voltage. Alternatively the 10BQ015 from International Rectifier (in the same package) can be used, or the more recent MBR0520LT1, a device with a low leakage current offered by ON Semiconductor in an SOD123 package.

The MAX6063 reference voltage generator, available in an SOT23 package, produces a precise output voltage of 3.000 V. The output noise is extremely low and no output capacitor is necessary. Its input voltage can be from 3.2 V to 12.6 V, and it has a negligible current consumption of 90 µA. If this boost converter circuit is used as part of a larger circuit, there will often be a reference voltage source already available which can of course be used instead of the MAX6063.

The inductor L1 is a tiny drum-core coil which can easily be made by hand. Be sure that the core material used is suitable for the switching frequency of the regulator. The DO1608C-103 by Coilcraft is ideal. In no circumstances should an ordinary suppressor choke be used.

Printed circuit board

When designing a printed circuit board it is essential to observe a ‘switching supply’ layout in order to keep the electromagnetic interference emissions as low as possible: SMD components, wide tracks kept as short as possible where high currents flow, and a ground plane on the underside of the board.

(020430-1)

Reference

The circuit is adapted from the article Extending Battery Life of a White Light LED Driver by Michael Day of Texas Instruments: the original is available on the Internet at www.chipcenter.com/analog/c071.htm.

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